LONG-RANGE FORECASTING OF STORMINESS OVER THE NORTHERN HEMISPHERE OCEANS

by

Elmar R. Reiter, Principal Investigator

and Bruce C. Macdonald

Department of Civil Engineering

Colorado State University

Fort Collins, CO

Final Report

ONR Grant N00014-86-K-0544

1 June 1986 - 31 December 1988

January 1989

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1. Scientific Accomplishments

The focus of research was directed toward "heavy weather at sea," specifically to marine "bombs" and their predictability. The approach to the research involved analyses of bombs which occur over land, in order to determine the key signatures of bomb development. The work was divided into two ~~separate~~ tasks:

1) A comprehensive diagnostic effort aimed at examining the nature of explosive cyclogenesis, including a comparison of bombs and nonexplosive, or regular, cyclones. The generation of vorticity, divergence, and latent heating patterns at the incipient, explosive, and mature phases of bombs were analyzed and compared to similar phases of regular cyclones.

2) A numerical modeling effort of the bombs and regular cyclones using the same cases studied as in the diagnostic effort. A "feature" component was developed and incorporated into an existing numerical model in order to improve the prediction of central sea level pressure in a bomb. The model was also used to examine the sensitivity of cyclogenesis to slight adjustments in the input data fields, and it was used to examine the trajectories of air parcels which were deemed to be important to explosive cyclogenesis.

Details of this work are largely covered in the dissertation prepared under this grant by Bruce C. Macdonald. The dissertation, entitled " Explosive Cyclogenesis over the Eastern United States," is included as an appendix to this report.

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1.1. Diagnostic Studies.

Because of the sparsity of meteorological data over the oceans, the research focused on continental bombs over the United States in order to find the crucial signatures which distinguish bomb development from the development of regular cyclones.

A total of seven bombs were identified during a six-year period. The bombs developed and reached their mature phases over the eastern United States, with the position of most explosive deepening generally over the central Mississippi Valley. One of the bomb cases involved the infamous Ohio blizzard of January 1978, in which the central sea level pressure reached 957 mb, with a 24-hour pressure drop of 40 mb. Twelve cases of regular cyclones were also examined. The regular cyclones moved across the eastern United States, with their intermediate phase occurring over the central Mississippi Valley. Analyses were prepared on a grid with 72 km resolution centered over the Mississippi Valley and using data interpolated from radiosonde soundings at every 50-mb level. The primitive equations, rewritten in terms of a vorticity tendency equation, a divergence tendency equation, and a thermodynamic equation were used to study the dynamics of explosive cyclogenesis. Three separate phases were identified for bombs: the incipient phase, the explosive phase and the mature phase. Each succeeding phase followed the previous phase by 12 hours. The regular cyclones were also divided into three phases, each separated by 12 hours: the incipient phase, the intermediate phase, and the mature phase.

Composite analyses of vorticity, vorticity tendency, divergence, and latent heating were performed for each phase of both the bombs and the regular cyclones. Both vertical profiles and horizontal or spatial composites were prepared. Each case was also analyzed in detail in order to determine the nature of critical signatures of development which might not show up on the composite analyses.

In many ways, both the diagnostic and modeling studies show that bombs are more intense versions of regular cyclones. There is a strong convergence in the lower troposphere around the center of a bomb, there is an intense core of upward vertical motion with a great deal of latent heating, and there is a pattern of strong divergence aloft. Bombs appear to

be driven more by "dry" processes in their early stages, but appear to be more dependent on latent heating for their final development into the most intense phase. Bombs develop along strong baroclinic zones and require a configuration of physical components similar to that in regular cyclones to bring about development. These components include vorticity advection in the upper troposphere, a conditionally unstable atmosphere, and a strong source of moisture. This research has focused on finding the distinct characteristics, or signatures, of bombs which may provide a key to both the understanding and prediction of bomb development. While one should obviously take careful note of the differences between bombs and regular cyclones, one should not lose sight of the fact that there are fundamental physical similarities between the two types of storms.

A series of vertical profiles over the surface position of the storm center was developed for each phase of each of the two classes of storms. The profiles revealed several important signatures of bomb development.

1. The vertical profile of vorticity in a bomb shows a rapid increase of vorticity in all layers of the troposphere as the storm progresses from its incipient through its explosive and mature phases. The greatest increases occur in the lower troposphere, especially below 700 mb. At all phases of bomb development, the relative maximum in vorticity remains in the lower troposphere, near 850 mb, with a relative minimum in the upper troposphere. In regular cyclones, the vorticity increases only slightly in the lower troposphere, with little difference in the middle and upper troposphere as the storms mature.

2. The vertical profile retains a distinctive vertical gradient in vorticity in the incipient and explosive phases. This gradient weakens somewhat during the mature phase. Regular cyclones also show relatively high vorticity values in the lower layers, but the vertical profile is dramatically different from that associated with a bomb. Relative vorticity values are nearly constant with height in the regular cyclones.

3. The vorticity tendency equation shows that the lower tropospheric increases result mainly from the convergence term for both the bombs and the regular cyclones,

but this term is stronger throughout a deep lower-tropospheric layer for the bombs. Upper-tropospheric vorticity is dominated by the advective terms and a nearly offsetting influence of the divergence term for both classes of storms. The magnitudes of these two terms are considerably stronger for the bombs than for the regular cyclones.

4 In the incipient and mature phases of a bomb, the lower layer of convergence is very deep, extending to 600 mb, and the upper layer of divergence is also very deep, indicating that there is a well-defined layer of nondivergence around 500 mb. As the bomb reaches a mature stage, this pattern weakens and tends to be confined to more shallow layers. The regular cyclones show a similar, but considerably weaker, vertical profile of convergence and divergence with an ill-defined layer of nondivergence.

5. During the most explosive growth phase of bomb development, the vorticity and geopotential (wind and mass) fields tend to remain largely in balance, with a slight imbalance promoting convergence in the lowest layers and divergence at jet stream levels. Estimates of total divergence tendency, without consideration of the frictional effects, show an indication for convergence at all levels. In regular cyclones the vorticity and mass fields are slightly out of balance at all tropospheric levels, tending to promote convergence at all levels.

6. Total latent heating tends to be much stronger for bombs than for regular cyclones, at all comparable phases of development.

7. Convective latent heating in bombs is strongest during the incipient phase and weakens during each of the later phases. The maximum heating occurs in the 600- to 750-mb layer for all phases.

8. Large scale latent heating in bombs is strong during all phases, but is most intense during the explosive phase. There appears to be a tendency for the level of maximum large scale heating to shift downward as the storm progresses from its incipient to

its mature phase. During the explosive and mature phases, the large scale heating is clearly stronger than the convective component.

9. Convective latent heating in regular cyclones shows very little change from phase to phase, with a slight maximum during the intermediate phase. Large scale latent heating in regular cyclones tends to increase slightly from the incipient to the mature phase, with the level of maximum heating shifting from 500 mb to around 750 mb during the same time period.

10. Convection is strongest in the area to the south and southeast of the storm center during the three phases of a bomb, but the large scale heating is well focused over the center of the storm, especially during the explosive and mature phases. Regular cyclones show a much more diffuse pattern of heating than the bombs.

11. Both bombs and regular cyclones show an increase in moisture content in the lower troposphere as the storms grow from the incipient to the mature phases. The bombs are considerably more moist than the regular cyclones at comparable phases, especially during the explosive and mature phases.

12. There appears to be little change in the static stability of a bomb during its three phases. This factor indicates that the tendency of a storm to shift to smaller scales, thus becoming more intense as the storm destabilizes, is not evident in the data.

13. The intrusion of stratospheric air into the storm core appears to be a very weak factor in generating vorticity, even at upper levels. The generation of vorticity in bombs, by this factor, is similar to that of the regular cyclones.

14. A distinct signature of a developing bomb appears to be evident in the upper half of the lower troposphere, between 850 and 600 mb. In this layer the convergence, vorticity, and generation of vorticity by convergence are especially strong for the bombs and are weak in the regular cyclones. There is generally a maximum in latent heating in this layer as well.

On a case-by-case basis there appear to be several important aspects of bombs in comparison to regular cyclones.

1. The upper level vorticity maxima, at 500 mb and 250 mb, appear to be nearly in phase with one another for the bombs, but in regular cyclones, the 250-mb maximum passes over the storm center ahead of the 500-mb maximum.

2. In the warm sector, to the east and southeast of a developing bomb, there appears to be a strong vorticity maximum associated with a relatively high moisture content and a strong moisture gradient in the lower troposphere from 950 to 800 mb. For regular cyclones, this maximum is weaker and the moisture content and gradients are less than those observed with the bombs. The vorticity maximum appears to be related to the existence of a low-level jet in the warm sector ahead of the storm. The identification of this jet streak and an estimation of its maximum winds or vorticity appear to be crucial components of predicting the development of a bomb.

1.2. Numerical Modeling Efforts.

A numerical model was applied to test the importance of several key components of cyclogenesis. A mesoscale "feature" is expressed mathematically and is used to capture the mutual adjustments in the geopotential, or temperature, fields and the wind fields. This feature allows the cyclones to intensify to a greater extent than in the nonfeature model, and it provides a more realistic prediction of central sea-level pressure for the bombs. For the regular cyclones, the feature model is able to predict the intensity of storms which intensify slightly, but if a storm weakens notably, the feature model erroneously maintains the strength of the storm.

The feature model generates realistic vorticity and divergence profiles for the bombs, correctly depicting the depth of the convergence and divergence layers and correctly predicting an increase in vorticity at all levels of a developing bomb. The vertical profiles of vorticity are predicted rather well also.

The model's ability to capture the relationship between the precipitation, or latent heating patterns, and the storm center appear to be crucial factors in predicting cyclone intensification. If the model predicts precipitation which is too intense near the center of the storm, the forecast central sea-level pressure will be too low. If the model's precipitation pattern is well removed from the storm center, the central sea-level pressure will be too high.

The model was used to generate trajectories of parcels of air which are initially located in the warm sector of an incipient storm. The results show that parcels of air which have high relative vorticity and which have high moisture content and are associated with strong moisture gradients tend to be drawn into a bomb. In the regular cyclone cases, the parcels, with similar but weaker characteristics, usually are not drawn into the storm. It is evident that the ambient vorticity and moisture fields, and their relationship to one another, play an important role in generating a bomb.

The model was used to test the relative importance of the vorticity and moisture fields in causing explosive cyclogenesis. A series of experiments was developed to provide smoothed or adjusted wind, height and moisture fields for input into the model. The results show that the decrease in vorticity by smoothing at upper levels has only a marginal effect on cyclogenesis. The upper-level vorticity advection and divergence are important components of bomb formation, but they do not appear to be limiting components.

A smoothed lower-level vorticity field also has a slight impact on cyclogenesis. As the vorticity maxima are reduced, the predicted central sea-level pressures will increase. An experiment in which the moisture gradient was shifted away from the predicted storm track indicated that the lower-level moisture is crucial in predicting storm intensification. The moisture content in the lower troposphere, and its position relative to the lower-layer vorticity pattern, appear to be the most important components of explosive cyclogenesis. A separate experiment in which the lower-layer moisture field was merely smoothed provided little change in the prediction of storm intensity.

These diagnostic and modeling studies provide a broad view of the nature of explosive growth of storms located over continents and along polar fronts, generally during the winter

months. It will be important to extend these efforts to include a larger sample of storms. Comparable analyses should be conducted for a separate population of bombs within polar air streams, and a separate analysis of explosive growth over the oceans. Perhaps the most important characteristics described here involve the nature of the intensification in the lower tropospheric layers, particularly between 850 mb and 600 mb over the storms. In addition, the importance of the ambient fields of vorticity and moisture in the lower layers, not immediately associated with an incipient storm, needs to be addressed in greater detail. The identification of a low-level jet streak in the warm sector appears to be a critical component of predicting explosive cyclogenesis. Numerical models will provide a valuable tool for investigating bomb growth, and the development of specific model components, such as "features," needs to be investigated more extensively.

1.3. Extension to Marine Bombs.

Both the diagnostic studies and the modeling efforts indicate that there are critical components of bomb development which must be examined in the marine cases. These include the low-level jet streak ahead of the storm, the position and strength of the low-level moisture gradients, and the strength and position of an upper level jet streak and trough which move over the developing storm. In the upcoming ERICA program, there should be a specific effort aimed at describing the low-level jet streak, probably through dropsonde measurements. In addition, the measurements should be aimed at depicting the lower tropospheric moisture field, including especially detailed measurements of the moisture gradients along the projected storm path. A separate effort should be aimed at improving the feature model with specific attention to the prediction of central sea level pressure associated with bomb development. Improvements should focus on the advection of the feature, on the capture of the latent heating pattern, and on retaining the sharpness and non-geostrophic components of the lower-level jet streak.

2. List of Publications.

Hu, Qi, and Elmar R. Reiter, 1987: A diagnostic study of explosive cyclogenesis in the lee of the Rocky Mountains. *Meteorol. Atmos. Phys.*, **36**, 161-184.

Macdonald, Bruce C. and Elmar R. Reiter, 1988: Explosive cyclogenesis over the eastern United States. *Mon. Wea. Rev.*, **116**, 1568-1586.

3. List of Presentations.

Sixth Conference on Ocean-Atmospher Interaction of the AMS, January 13-17, 1986, Miami, Florida. Bruce C. Macdonald and Elmar R. Reiter – "Large Scale Ocean-Atmosphere Interaction Deduced from Principal Component Analyses."

Eleventh Conference on Weather Forecasting and Analysis, June 17-20, 1986, Kansas City, Missouri. Bruce C. Macdonald and Elmar R. Reiter – "Diagnostic Studies of the Role of Convection and Upper-Level Features in Explosive Cyclogenesis."

ERICA Workshop, September 15-18, 1986, Drexel University, Philadelphia, PA – Elmar R. Reiter, "Oceanic Cyclogenesis."

Institute for Naval Oceanography, NSTL, Mississippi, March 4-6, 1987 – Elmar R. Reiter presented an invited seminar.

DAIMS Workshop, NSTL, Mississippi - Elmar R. Reiter. Presentation on numerical modeling.

Expert Systems Technology in the ADP Environment, November 2-3, 1987, Washington, D.C. Elmar R. Reiter – "Decision-Support Architecture for the Portable, Interactive Weather Prediction System (PWIPS)." Sponsored in part by the Navy Regional Data Automation Center.

ITD, Mississippi State University, Jackson Mississippi, June 29-30, 1987, Elmar R. Reiter presented an invited seminar.

In Washington, D.C. December 1-5 1986, December 14-19, 1986 and March 1-3, 1987, Seminars to DoD (ONR, NRL, SPAWAR).

4. List of Awards.

E. R. Reiter: Distinguished Visiting Professor, University of Alaska. Participation in the design of an interdisciplinary research program for air-sea interaction in the Bering Sea and Gulf of Alaska.

5. Number of Graduate Students Supported.

1988: Qi Hu - part time; James F. Bresch – part time; Bruce C. Macdonald – part time.

1987: Qi Hu - full time; James F. Bresch – part time; Bruce C. Macdonald – part time.

1986: Qi Hu - full time; Bruce C. Macdonald – part time.

1985: Qi Hu - full time; Bruce C. Macdonald – part time.

6. Number of Graduates and Their Theses.

Qi Hu, Master of Science – 1986 – A Diagnostic Study of Explosive Cyclogenesis in the Lee of the Rocky Mountains.

Bruce Macdonald, Doctor of Philosophy – 1988 – Explosive Cyclogenesis over the Eastern United States.

7. Number of Minority and/or Women Students:

One minority Qi Hu, graduated 1986, M.S., Includes work on his Ph.D.

8. Idea for Future Research.

Modeling of severe cyclogenesis over oceans, using "features" as described in this report, as well as "expert systems" to help identify such "features" from proxy data.